B-ball Dark Matter and Baryogenesis

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Abstract

It has been recently suggested that stable, supersymmetric B-balls formed in the early universe could not only be the dark matter at the present epoch, but also be responsible for baryogenesis by their partial evaporation at high temperatures. We reinvestigate the efficiency of B-ball baryogenesis and find it to be limited by the diffusion of baryon number away from the B-balls. Successful baryogenesis may only occur for B-balls with charges $Q \lesssim 10^{20} - 5 \times 10^{23}$, which is close to the observational lower limits on the Q of a significant B-ball dark matter component. We also present some cosmological constraints on the abundances of larger B-balls in the early universe.

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It is well known that particle physics models containing an unbroken U(1) symmetry allow for the existence of non-topological solitons [1,2], i.e. Q-balls, which carry a large number of a conserved global charge [3]. If the effective potential $U(\Phi)$, of the scalar Φ carrying the global charge grows slower than the second power of Φ, the mass of the solitonic object scales with the U(1) charge Q as $M_Q \approx \tilde{M}\, Q^p$ $(0 < p < 1)$, where $\tilde{M}$ is some energy scale. The minimal supersymmetric standard model (MSSM) with supersymmetry breaking communicated at low energy scale contains an effective potential which is nearly flat $\sim M^4$ at large Φ. In this case, $M_Q \approx M\, Q^{3/4}$, where $M \approx 1 - 10$ TeV is the SUSY breaking scale [3]. Such Q-balls are absolutely stable at zero temperature if their mass M_Q becomes smaller than the total mass of individual U(1) charged particles $m\, Q^1$. Moreover, large baryonic Q-balls may be efficiently produced in the early universe [4,5] within a scenario of a collapsing unstable Affleck-Dine condensate [6]. In the MSSM the role of the global charge is played by baryon or lepton number carried by squarks or sleptons respectively [7]. Whereas L-balls (carrying leptonic charge) are not expected to survive until the present epoch for $Q \lesssim 10^{36} (M/\mathrm{TeV})^{4/5}$ due to emission of massless neutrinos, B-balls (containing baryonic charge) with $Q \gtrsim 10^{12}\, (M/\mathrm{TeV})^4$ are

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stable because of the largeness of the nucleon mass. It has thus been proposed that B-balls produced in the early universe are not only an attractive dark matter candidate but may also be responsible for baryogenesis via partial evaporation of B-balls in the early universe [8]. (This is distinct from a scenario of evaporation of unstable B-balls [9] which could be responsible for baryogenesis and the creation of neutralino dark matter.)

In this paper we reinvestigate the evaporation of B-balls. We find the efficiency of this process to be limited by the transport of baryon number away from the soliton, resulting in somewhat different conclusions than drawn in prior work [8]. We also give some previously unmentioned cosmological limits on the abundances of B-balls.

B-balls may release baryonic charge via evaporation of squarks at temperatures $T > m_\chi$, where m_χ is the squark mass [8]. Assuming that B-balls constitute dark matter at present (with fractional contribution to the critical density of Ω_Q), there number density n_Q in the early universe at temperature T has been

$$n_Q \approx 0.8 \times 10^{-9}\, g_* \frac{m_p}{M} \frac{\Omega_Q}{Q^p} T^3 \,. \tag{1}$$

Here m_p is proton mass, g_* is the number of relativistic degrees of freedom at the considered epoch ($g_* = 3.909$ today), and we have assumed a Hubble constant of $H = 70 \ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. Consider B-balls with the general properties for their mass

$$M_Q = \alpha M Q^p \tag{2}$$

and their radius

$$R_Q = \beta M^{-1} Q^{p/3} \,. \tag{3}$$

For an essentially flat effective potential (e.g. $U \to M^4$) for $\Phi \gg m_\chi$ the coefficient $p = 3/4$ [3] and the numerical factors may be computed for large B-ball charge: $\alpha \approx (4\pi/3)\sqrt{2}$, $\beta \approx 1/\sqrt{2}$ [8]. If, on the other side, the expression $U(\Phi)/\Phi^2$ has a minimum at finite Φ then the B-ball mass scales with $p = 1$ [2].

To trace the baryon evaporation rate of a population of B-balls at high temperatures, we consider the thermodynamical properties of a volume element containing only one B-ball. Let Q be the charge of the B-ball surrounded by N_B baryon number carrying particles in the diffuse plasma in a volume V, such that the total charge in the volume element is $N_{\mathrm{tot}} = N_B + Q$. Then the

Helmholtz free energy of the system reads as follows

$$F = -VT^4 \frac{7\pi^2 g_B}{360} + \frac{3N_B^2}{g_B VT^2} + \alpha M Q^p \ , \tag{4}$$

where g_B is the number of baryon charge carrying degrees of freedom and where we assumed a vanishing entropy, $S_Q \approx 0$, for the B-ball. Expression (4) further assumes that baryon number in the plasma is carried by fermionic relativistic degrees of freedom (cf. [10]). For fixed $N_{\rm tot}$, V, and T such a configuration has to minimize the Helmholtz free energy Eq. (4) in thermal and chemical equilibrium. This extremum may be obtained by varying the fraction of $N_{\rm tot}$ residing in the B-ball. One thus finds that only for charge density in excess of

$$\frac{N_{\rm tot}}{V} \gg \left(\frac{g_B}{6}\alpha M T^2\right)^{1/(2-p)} V^{(p-1)/(2-p)} \tag{5}$$

the existence of a B-ball is thermodynamically favorable. In this case the B-ball carries almost the entire charge of the volume element ($Q \sim N_{\rm tot}$). Nevertheless, in chemical equilibrium a small fraction of baryon number also resides in the plasma, with baryonic density

$$n_B^{\rm eq} = \frac{g_B}{6} p\alpha M T^2 Q^{p-1} \, . \tag{6}$$

We stress that by constraining our considerations to the thermodynamics of a finite domain with volume V and baryon number $N_{\rm tot}$ we have not obtained the absolute minimum for the free energy. Considering a larger domain, but with $N_{\rm tot}/V$ kept fixed, one may always find a state of lower Helmholtz free energy. This is also exemplified by the odd dependence of Eq. (5) on volume (except for $p = 1$). As already noted in [8], in the extreme limit the lowest free energy state is reached when all the baryon number of the universe is contained in one large B-ball.

Nevertheless, considerations of partial chemical equilibrium are appropriate for the initial conditions envisioned resulting from the breakup of an Affleck-Dine condensate. Here B-balls of typical initial charge Q_0 form, with negligible baryon number in the plasma [11]. During the subsequent evolution of the universe the coalescence of B-balls is not possible, such that a state of even lower Helmholtz free energy is not attainable, and only partial chemical equilibrium between an individual B-ball and the plasma around it may be attained. Following similar arguments Laine & Shaposhnikov [8] estimated the baryon evaporation rate of B-balls via squark emission at high T by

$$
\begin{aligned}
\Gamma_{\rm evap} \equiv \frac{dQ}{dt} &= -\kappa(\mu_Q - \mu_{\rm plasma})T^2\, 4\pi\, R_Q^2 \\
&\approx -\kappa'\, 4\pi\, R_Q^2\, n_B^{\rm eq} \quad \text{for} \quad \mu_{\rm plasma} << \mu_Q\,,
\end{aligned} \tag{7}
$$

where μ_Q is the chemical potential of the B-ball. The second line of Eq. (7) is operative under the assumption that the evaporated particles can be quickly transported away from the B-ball surface in order to sustain a jump between chemical potentials of the B-ball and the plasma ($\mu_Q - \mu_{\rm plasma} \neq 0$). Note that $\mu_Q = \mu_{\rm plasma} = (p/6)\alpha M Q^{p-1}$ in chemical equilibrium. The constants κ and κ' in Eq. (7) are $\lesssim 1$, where for $\kappa' \approx 1$ the evaporation rate is at its physical upper limit, implying there is no dynamical suppression of the evaporation and accretion of squarks, i.e. every squark approaching a B-ball will be absorbed. This is in contrast to the evaporation of quarks from B-balls which is suppressed [12] and thus of negligible importance. Nevertheless, baryon transport away from the B-ball is not as efficient as envisioned in Ref. [8]. Baryons released from the B-ball surface, will establish chemical equilibrium with the B-ball, if they are not able to escape the surface layer and evaporation ceases.

The transport mechanism of baryon number is by diffusion of squarks and quarks in the hot plasma. Solving the spherical diffusion equation with diffusion constant D

$$
\frac{\partial n_B(r,t)}{\partial t} = D\frac{1}{r}\left(\frac{\partial^2}{\partial r^2} r\, n_B(r,t)\right)\,, \tag{8}
$$

on the condition that the number density at the surface boundary does not change with time ($n_B(R_Q,t) = n_B^{\rm eq}$), yields a steady-state solution for the density n_b. We confirmed this result numerically for all radii $r \lesssim L_{\rm d}$, where $L_{\rm d} \approx \sqrt{D\,t}$ is the diffusion length at time t. Therefore the particle flux through the B-ball surface is constant and given by

$$
\Gamma_{\rm diff} \equiv \frac{dQ}{dt} = -4\pi\, k\, R_Q\, D\, n_B^{\rm eq} \tag{9}
$$

where the diffusion constant of relativistic squarks and quarks in a hot plasma is $D \approx a\,T^{-1}$ with $a \approx 6$ for quarks and $a \approx 4$ for squarks, respectively [13,14]. We have determined the numerical constant k to be very close to unity, such that we will drop it in what follows. Apart from the numerical results the expression (9) can be motivated by assuming a constant flux $dQ/dt = 4\pi\, R_Q^2\, \partial n/\partial r$ and approximating $\partial n/\partial r$ by $n_B^{\rm eq}/\Delta r$. The only time independent lengthscale in this system is the B-ball radius R_Q, so $n_B^{\rm eq}/\Delta r = n_B^{\rm eq}/R_Q$.

By comparing the rates (7) and (9)

$$
\Gamma_{\rm diff}/\Gamma_{\rm evap} = \frac{D}{\kappa'\, R_Q} \sim \frac{M}{T} Q^{-p/3} \tag{10}
$$

it is obvious that, for large B-balls, the diffusive transport is orders of magnitude less efficient than the evaporation of baryons from the B-ball. Since the evaporated baryons are still within the surface layer of the B-ball, the B-ball is at close to chemical equilibrium with the surrounding plasma and the charge emission rate (7) must be replaced by (9).

Evaporation of squarks from B-balls is only efficient for temperatures above the squark mass $m_\chi \approx 0.1 - 1$ TeV. For temperatures below this mass the evaporation rate is exponentially suppressed by the Boltzmann factor $\exp(-m_\chi/T)$. By integrating Eq. (9) one may calculate the number of emitted baryons from a single B-ball until evaporation becomes inefficient at temperature $T_{\rm fin} \approx m_\chi$

$$\Delta Q \approx b \, \frac{M_0}{T_{\rm fin}} Q_0^{\frac{4}{3}p-1} \, . \tag{11}$$

Here Q_0 is the initial B-ball charge, and $M_0 = (90/32\pi^3 g_*)^{1/2} M_{\rm Pl} \approx 3.7 \times 10^{18}/\sqrt{g_*(T_{\rm fin})}$ GeV is given by the time-temperature relation $t = M_0 \, T^{-2}$ during a radiation dominated universe with $g_*(T_{\rm fin}) \approx 200$. Note that for the interesting case $p = 3/4$ the numerical constant in Eq. (11) $b = (4\pi/3) \, g_B \beta a p \alpha \approx 4.7 \times 10^3$, assuming $g_B \approx 72$, and ΔQ is independent of the initial charge of the B-ball. To ensure that an initially formed B-ball survives evaporation until present ($\Delta Q/Q_0 \ll 1$), such a B-ball must have an initial charge of $Q_0 > 10^{18} - 10^{19}$.

Within a B-ball baryogenesis scenario the number density of baryonic matter n_B and the number density of B-balls are related by

$$n_B = n_Q \, \Delta Q \, . \tag{12}$$

Combining Eq. (11), (12) and Eq. (1) one may calculate the baryon-to-photon ratio at the present epoch

$$\eta = \frac{n_B}{n_\gamma} \approx 1.3 \times 10^{-8} b \, \frac{m_p}{M} \frac{\Omega_Q}{Q_0^{1-\frac{1}{3}p}} \frac{M_0}{T_{\rm fin}} \, . \tag{13}$$

For a B-ball with $p = 3/4$, $M \sim 1 - 10$ TeV, and $T_{\rm fin} \sim 0.1 - 1\,$TeV it is necessary to have $Q_0 \gtrsim 9 \times 10^{20} - 4 \times 10^{23}$ to obtain a baryon-to-photon ratio of $\eta \approx 3 \times 10^{-10}$. This should be compared to the range $Q_0 \sim 10^{22} - 10^{28}$ quoted in Ref. [8]. (Note that the above estimate has also very different dependence on the parameters M and $T_{\rm fin}$ than the estimate by Ref. [8].) It is intriguing that the range of B-ball charges which may yield successful baryogenesis is very close to the observational lower limits $Q \gtrsim 10^{21} - 3 \times 10^{22}$ on the charges of a significant B-ball galactic halo dark matter population [15].

A few comments concerning very large Q-Balls are of relevance. There are no detector limits on large B- and L-balls, either since their current flux is extremely small, for stable solitons, or since they did not survive to the present epoch, in the unstable case. There are, however, some constraints on the existence of large Q-Balls in the early universe. Consider first unstable ($p = 1$) B-balls. During their decay they produce baryon inhomogeneities which may lead to a scenario of inhomogeneous nucleosynthesis. It is well known [16,17], that baryon lumps with baryon number in excess of

$$N_b \gtrsim 10^{35}(\eta_l/10^{-4})^{-1/2} \quad (\eta_l \gg 10^{-10}) \tag{14}$$

can not homogenize by neutron diffusion before the epoch of weak freeze-out. Here η_l is the baryon-to-photon ratio in the baryon-rich region, and the value of 10^{-4} is of particular relevance. It is expected that immediately after the B-ball decay $\eta_l^i \gg 10^{-4}$ (where we assume that baryon number is in form of diffuse baryons). Neutrino heat conduction will subsequently expand the baryonic lump to an asymptotic $\eta_l \approx 10^{-4}$, independent of η_l^i, unless the baryonic B-ball charge is in excess of $N_b \gtrsim 10^{44}\eta_l^i$ [17]. If a fraction $f_b \gtrsim 10^{-2}$ of all baryons resides in such baryon number enhanced regions, overproduction of ^{4}He during nucleosynthesis results. For $N_b \gtrsim 10^{44}\eta_l^i$ similar constraints from ^{4}He overproduction apply, but here even more stringent constraints may be derived from a possible overproduction of heavy elements. It is interesting to note, that for $f_b \lesssim 10^{-2}$ B-balls with $N_b \gtrsim 10^{35}$ may yield to the production of a primordial metallicity, without violating observational constraints on the light element abundances [18].

A more speculative constraint may apply for large stable B-balls. If their charge is in excess of $Q \gtrsim 10^{44}\Omega_Q^{4/3}(M/\mathrm{TeV})^{-4/3}$ their mean separation ($n_Q^{-1/3}$) at the QCD transition at temperature $T \approx 100\,\mathrm{MeV}$ is $\gtrsim 1\,\mathrm{m}$. In the case of a first-order QCD phase transition they may act as seeds for the nucleation of hadronic phase. Depending on the amount of supercooling which quark-gluon plasma may sustain before spontaneous nucleation is efficient, and thus on the (three) surface free energies between the participants, hadronic phase, quark-gluon phase, and B-balls, hadronic phase bubbles may only form around B-balls. If this is the case, the mean separation of baryon number enhancing quark-gluon plasma bubbles towards the end of the transition is such that baryon number inhomogeneities with $N_b \gtrsim 10^{35}$ of individual lumps (the baryon number within $\sim 1\,\mathrm{m}$ at $\eta \approx 3 \times 10^{-10}$) is large enough to yield a scenario of inhomogeneous nucleosynthesis. Except for very narrow ranges in parameter space such a scenario is typically in conflict with observationally determined light element abundances.

In summary, we have reinvestigated a proposed scenario of baryogenesis by the partial evaporation of stable B-balls in the early universe. Under the assumption that the B-balls are the dark matter at the present epoch, we have

found that a successful baryogenesis scenario by B-ball evaporation at high temperature requires B-balls with baryon number $Q \approx 10^{20} - 5 \times 10^{23}$, which is close to the observational lower limit on the charges of a significant ($\Omega_Q \approx 1$) galactic B-ball population. Thus, if stable B-balls are responsible for baryogenesis, and they constitute the dark matter, they could be detected in the immediate future. We have also given some limits on the existence of larger B-balls in the early universe.

References

[1] R. Friedberg,T.D. Lee and A. Sirlin, Phys. Rev. **D 13** (1976) 2739

[2] S. Coleman, Nucl. Phys. **B262** (1985) 263

[3] G. Dvali and A. Kusenko and M. Shaposhnikov, Phys. Lett. **B417** (1998) 99

[4] A. Kusenko and M. Shaposhnikov, Phys. Lett. **B418** (1998) 46

[5] K. Enqvist and J. McDonald, Phys. Lett. **B425** (1998) 309

[6] I. Affleck and M. Dine, Nucl. Phys. **B249** (1985) 361

[7] M. Dine, L. Randall and S. Thomas, Nucl. Phys. **B458** (1996) 291

[8] M. Laine and M. Shaposhnikov, Nucl. Phys. **B532** (1998) 376

[9] K. Enqvist and J. McDonald, Nucl. Phys. **B538** (1999) 321

[10] G.M Fuller, G.J. Mathews and C.R. Alcock, Phys. Rev. **D 37** (1988) 1380

[11] S. Kasuya and M. Kawasaki, Phys. Rev. **D 61** (2000) 041301; S. Kasuya and M. Kawasaki, hep-ph/0002285

[12] A. Cohen, S. Coleman, H. Georgi and A. Manohar, Nucl. Phys. **B272** (1986) 301

[13] M. Joyce, T. Prokopec and N. Turok, Phys. Rev. **D 53** (1996) 2930

[14] H. Davoudiasl and E. Westphal, Phys. Lett. **B432** (1998) 128

[15] A. Kusenko, hep-ph/9808276 and references hierin

[16] J. H. Applegate, C. J. Hogan, and R. J. Scherrer, Phys. Rev. **D 35** (1987) 1151

[17] K. Jedamzik and G. M. Fuller, Astrophys. J. **423** (1994) 33

[18] K. Jedamzik, G. M. Fuller, G. J. Mathews, and T. Kajino, Astrophys. J. **422** (1994) 423